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ANALYTICAL STUDY OF
FLOW REDUCTION DUE TO OXIDATION
OF WIRE-FORM POROUS SHEET FOR
TRANSPIRATION COOLED TURBINE BLADES

by Albert Kaufman

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Cleveland, Ohio*



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Cyclic and static oxidation data for wires of N155, Driver-Harris 242, TD nickel-chromium, and Hastelloy X from 1400⁰ F (1033 K) to 2000⁰ F (1367 K) were used to determine flow reduction effects for pore diameters from 10 to 100 μm and exposure times up to 600 hours. Analytical results were compared with experimental flow reduction data for oxidized wire-form porous sheets from other investigators. Conclusions were drawn as to the suitability of these materials for transpiration cooling with a metal temperature of 1800⁰ F (1255 K).

ANALYTICAL STUDY OF FLOW REDUCTION DUE TO OXIDATION OF WIRE-FORM POROUS SHEET FOR TRANSPIRATION COOLED TURBINE BLADES

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SUMMARY

An analytical study was made to evaluate the flow reduction characteristics due to the oxidation of wire-form porous sheet for metal temperatures from 1400°F (1033 K) to 2000°F (1367 K). The study was undertaken in order to provide a simple method for evaluating the ability of porous materials to meet the design requirements of transpiration cooled turbine blades in advanced air breathing engines. Four alloys were investigated, namely N155, Driver-Harris 242, TD nickel-chromium, and Hastelloy X. Analytical curves were derived from existing experimental measurements of oxidized wire specimens and compared with experimental oxidation data on porous materials from other investigators. In general, the analytical results agreed fairly well with the experimental data. None of the candidate alloys possessed sufficient oxidation resistance at 1800°F (1255 K) to be utilized in wire-form porous structures. It appears possible, however, to use some of these materials by preoxidizing them until an oxidation stable porous structure is attained.

INTRODUCTION

An analysis is made of the effects of oxidation on the flow reduction of wire-form porous sheets fabricated from four alloys being considered for transpiration cooling of gas turbine blades.

Advanced air breathing engines with turbine inlet gas temperatures in excess of 2500°F (1644 K) and compressor discharge temperatures in excess of 1000°F (811 K) will require turbine blade cooling of high effectiveness. The most readily available source of coolant is compressor discharge air. It has been shown in reference 1 that transpiration cooling where air is diffused through a blade wall containing fine, closely

spaced pores is theoretically the most efficient cooling method compared to convection and film cooling. The superiority of transpiration cooling over other methods arises from (1) the large surface area within the wall that the air can contact which enables it to effectively remove heat absorbed by the metal and (2) the insulating effect of the film formed around the blade when the air is ejected into the gas stream.

Two common processes for fabricating wire form porous sheets for transpiration cooling are weaving and winding. Rolling and sintering processes bring these sheets to the desired permeability and thickness.

The main problem in applying these porous materials to turbine blade cooling is the susceptibility of the small pores to closure by oxidation at elevated temperatures. Once significant oxidation starts it can become catastrophic in a short time since any restriction of the airflow will cause the metal temperature to rise and probably accelerate the oxidation process. The pore closure problem due to oxidation can be alleviated by increasing the size of the individual pores while spacing them farther apart to maintain the required permeability. However, if the pore size is increased too much, the cooling effectiveness will be reduced because of reduced wall internal surface area for the coolant to contact. If carried too far, this can result in overcoming the oxidation problem at the cost of losing the advantage of transpiration cooling over other cooling methods. There are also definite fabrication limitations to enlarging the pores of wire-form porous materials while trying to keep a constant permeability value.

The wire-form porous shells lack sufficient high temperature strength and rigidity to bear the centrifugal and gas forces in turbine blades. Internal struts are required to support the shells. The best nickel or cobalt base superalloys used for turbine blades can operate at temperatures near 1800°F (1255 K) with reasonable lives at normal cruise conditions for advanced air breathing engines. These alloys have been applied to cast convection cooled blades but can also be used for strut-supported blades.

One of the most commonly used alloys for wire-form porous materials, N155, has been limited because of oxidation characteristics to metal temperatures of 1350°F (1005 K) for turbine blading (ref. 2). This would mean that the strut for such a transpiration cooled blade would be operating several hundred degrees below its temperature capability based on strength properties. In order for transpiration cooling to be competitive with convection cooling for turbine blades the oxidation resistance of the porous material will have to be improved to the point where metal temperatures of about 1800°F (1255 K) can be sustained for a prolonged period.

The purpose of the study made herein was to derive a method of predicting the effects of flow reduction from oxidation of wire-form porous sheets over a wide range of permeabilities; the prediction was to be based upon existing experimental data. These data were from reference 3, which was an investigation of the oxidation of possible transpiration cooling materials in the temperature range from 1400°F (1033 K) to

2200⁰ F (1478 K). Wire diameter changes due to cyclic and steady-state oxidation were used as a basis for calculating the flow reduction due to closure of pores with initial diameters from 10 to 100 micrometers. The four materials considered were N155, TD nickel-chromium, DH242, and Hastelloy X. The oxidation conditions studied were for temperatures from 1400⁰ F (1033 K) to 2000⁰ F (1367 K) at exposure times up to 600 hours. The analytical results were compared with experimental results from other investigators.

PROCEDURE

Wire Specimen Oxidation Tests

Results of wire specimen cyclic and static oxidation tests from reference 3 are shown in table I.

Of the four materials which were investigated, N155 is an iron base alloy previously used extensively in transpiration cooling research, TD nickel-chromium is a thoria dispersion strengthened nickel base alloy having the nickel-chromium composition of nichrome heating elements, DH242 is another nickel base alloy with a composition similar to nichrome except for the addition of 1 percent columbium, and Hastelloy X is a nickel base superalloy. The nominal compositions of these alloys are shown in table II. Cyclic tests were conducted by exposing the specimens to test temperatures from 1400⁰ F (1033 K) to 2200⁰ F (1478 K), in a furnace with an air atmosphere and removing them after total time intervals of 4, 16, 64, 100, 200, 300, 400, 500, and 600 hours. In the static tests, the specimens were exposed to the test temperature continuously for 100 hours. After removal the specimens were air cooled to room temperature and the total oxide weight gain, spall loss, change in wire diameter, and mechanical properties were determined. The test apparatus and procedure are described in detail in reference 3. Only the wire diameter measurements are pertinent to this investigation. The cyclic and static-wire diameter data shown in table I represent optical measurements on metallographic sections of wire specimens for each condition of temperature and exposure time. An adjusted wire diameter increase is indicated in the table; this adjusted diameter will be discussed in the following section.

Analytical Method

The radial growth of the oxidation layer is assumed to be independent of the wire size up to the point at which complete internal oxidation takes place. Therefore, the

pore closure due to oxidation can be related to the changes in wire diameters given in table I.

The cyclic oxidation data of table I show generally equal or smaller wire diameter changes than the static data. In the cases where the wire size changes are smaller for the cyclic data than for the static data, it is believed a greater amount of spalling of the wire occurred. The greater spalling is probably a result of the intermittent heating and cooling that resulted from the cyclic test procedure. In actual wire-form porous sheet subjected to cyclic oxidation, it is believed logical to expect that some of the spall would be trapped within the sheet and contribute to the clogging of the pores. On the other hand, if it is assumed that some of the spall is extremely small, perhaps of the order of several micrometers in diameter, some of the spall could be expected to pass through the porous sheet. It is not within the scope of this report to study the effects of clogging from spall, but only to consider the clogging effect of an increase in wire size due to oxidation.

For the purposes of this report it is believed that the increase of wire size in wire-form porous sheet would be greater than that shown by the cyclic test data and less than that shown for the static test data of table I. Because of the lack of detailed information regarding the manner in which oxide forms, spalls and becomes entrapped within wire-form porous sheet, it was arbitrarily decided to use an average of the change in wire size as indicated by the cyclic and static data in table I. However, this can only be done for 100 hours exposure time with the data of reference 3 since these are the only static oxidation results available. Therefore, the cyclic oxidation data of table I were adjusted wherever possible by multiplying the wire diameter changes by a factor determined from the 100-hour exposure time average of cyclic and static data. As an example, if the cyclic and static oxidation wire diameter changes were 0.0001 inch (0.0025 mm) and 0.0003 inch (0.0076 mm), respectively, the average would be 0.0002 inch (0.0051 mm), and the cyclic data at other exposure times would be multiplied by a factor of 2 to obtain the adjusted values. The rate of oxidation for DH242 at 2000^o F (1367 K) was so rapid that the slight difference at 100 hours between cyclic and static data (0.0006- against 0.0005-in. diam increase) were not considered significant and a multiplication factor of 1 was therefore used. The oxidation of the N155 wire at 2000^o F (1367 K) reported in reference 3 was so severe that this case was not considered of any practical importance and was ignored in this study. Adjustments had to be made to the 1600^o F (1144 K) results for N155 and Hastelloy X since no wire diameter changes were measured after 100 hours of cyclic oxidation and, therefore, no multiplication factor could be determined. These adjustments were based on the nature of the data. For N155 at 1600^o F (1144 K) a multiplication factor of 1 was estimated since this factor was used for the 1400^o F (1033 K) and 1800^o F (1255 K) results and exposure times under 400 hours were neglected. For Hastelloy X at 1600^o F (1144 K), a multiplication factor of 1.5 was used

since factors of 1 and 2 were used for the 1400° F (1033 K) and 1800° F (1255 K) data, respectively, and exposure times under 400 hours were neglected.

The analysis is based on the assumption that because of the small pore sizes that usually exist in wire-form porous sheet the effect of oxidation in restricting the airflow can be represented by a capillary flow relation where the volumetric flow rate is proportional to the diameter of the capillary to the fourth power as shown in reference 4. This capillary effect is combined with an oxidation model where the pores in woven or wound wire-form sheet are assumed to be circular and that the rims of these holes are bounded by the outer surfaces of wires. In such a model any increase in the diameter of the wires forming the hole rim would be an equivalent decrease in the diameter of the pore. Thus, if d_o is the initial diameter of a pore and t is the increase in wire diameter at the temperature and time shown in table I, the final pore diameter, d , is $d_o - t$ and the percent reduction in flow from oxidation is given by

$$\left[1 - \left(\frac{d}{d_o} \right)^4 \right] \times 100$$

or

$$\left[1 - \left(\frac{d_o - t}{d_o} \right)^4 \right] \times 100 \quad (1)$$

It is recognized that the actual pore geometries in wire-form porous sheet are not circular but are odd-shaped, being formed by surfaces of woven or wound flattened wires. This analytical method of predicting flow reduction caused by oxidation will be verified by comparison with experimental studies conducted by other investigators on wire-form porous sheet.

The adjusted values of wire diameter change shown in table I were used for calculating flow reduction using equation (1). The exposure time assigned to each adjusted value other than zero is the average of the first and last exposure time over which it occurred. Thus, if the same adjusted diameter is shown for 100, 200, 300, and 400 hours, an average between 100 and 400 hours or 250 hours is used. These corrected values are presented in figure 1 as functions of exposure time for each temperature. The curves of figure 1 are used in the calculation of the flow reduction due to oxidation.

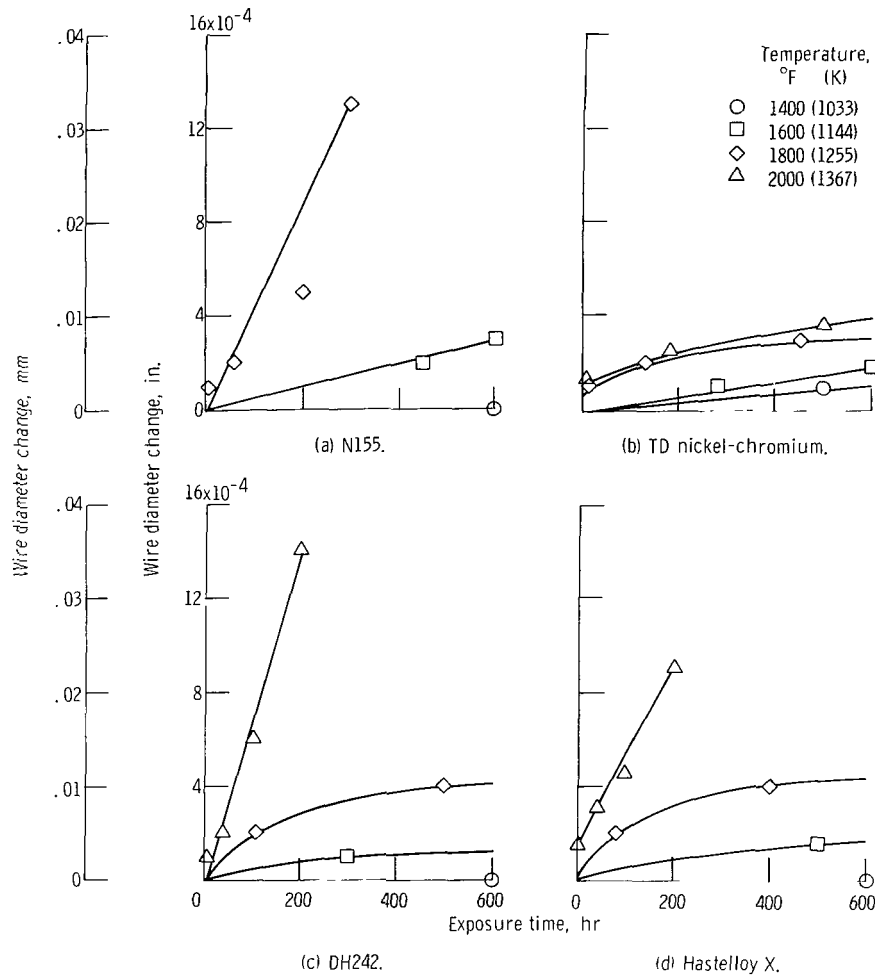


Figure 1. - Effect of exposure time on adjusted wire diameter increase.

DETERMINATION OF PORE SIZE

The permeability of porous materials has been expressed by several methods in the literature. One method has used a permeability coefficient K' that is a function of flow rate, temperature, air viscosity, and the pressures on the supply and discharge sides of the porous materials. The coefficient K' is determined for a standard set of conditions where the pressure drop through the porous material is 10 psi (N/cm^2) discharging to standard sea level conditions. Another method of specifying permeability is to use the same test conditions as specified above to define the resulting flow rate through the porous material in standard cubic feet per minute per square inch (scfm/ $in.^2$).

For materials of a given thickness and made by a given process the permeability specified by the above methods can be related to the pore size in the material. For this investigation this is more straightforward and the results better understood to work with pore sizes rather than other methods of specifying permeability. In order to use equation (1) an initial pore diameter d_0 has to be determined. It is impractical to make direct physical measurements because of the wide variation in pore sizes and shapes in a wire-form porous material. However, the pore diameters can be based on the efficiency of these materials as filters. A method of doing this is to flow a fluid containing glass beads of known diameters through the porous structure. The diameter of the largest bead to pass through the filter is called the "absolute filtration rating." This parameter was used as the initial pore diameter for the purposes of this analysis.

A relation between the absolute filtration rating and the airflow rate through wound porous material made from 0.005- and 0.010-inch- (0.127- and 0.254-mm-) diameter wire are presented in figure 2. The two data points shown are unpublished bead test data provided by the Filter Division of Bendix Corporation.

An analysis of the flow rates that would be required for an advanced air breathing engine in the 50 000-pound- (222 411-N-) thrust class indicated that the required permeabilities for turbine blades would result in flow rates from about 0.86 to 4.8 scfm/in.²

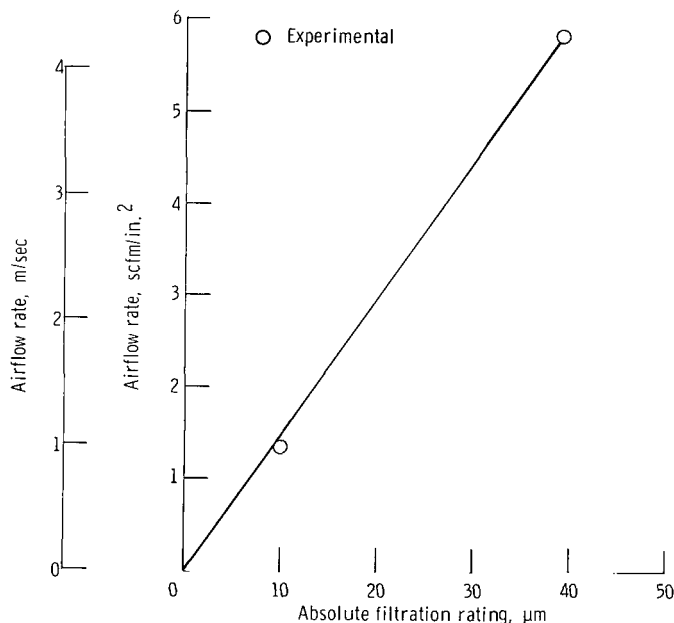


Figure 2. - Filtration rating - airflow rate relation for wound wire-form porous sheet, based on Bendix bead tests. Flow rates based on inlet pressure of 24.7 psia (17.0 N/cm²), discharge pressure of 14.7 psia (10.1 N/cm²), and air temperature of 70 °F (294 K).

(0.63 to 3.5 m/sec) based on standard conditions of 24.7 psia (17.0 N/cm^2) inlet pressure, 14.7 psia (10.1 N/cm^2) discharge pressure, and 70° F (294 K) air temperature. As shown in figure 2, the absolute filtration rating for the flow rates indicated above ranges from about 6 to 32 micrometers.

RESULTS AND DISCUSSION

Calculated Effect of Oxidation on Flow Rate

The calculated effects of oxidation at 1400° F (1033 K), 1600° F (1144 K), 1800° F (1255 K), and 2000° F (1367 K) are shown as a function of time up to 600 hours for porous materials of N155, TD nickel-chromium, Driver-Harris 242, and Hastelloy X are shown in figures 3(a) to (e). The oxidation effects are in terms of the percent of flow reduction calculated from the capillary flow relation, and the data of figures 1 and 2 and the results are presented for initial pore diameters of 10, 20, 30, 40, and 100 micrometers.

The N155 material shows no significant oxidation at 1400° F (1033 K) for all initial pore diameters. The results seem to corroborate the statement made in reference 2 that N155 has a complete lack of oxidation at 1350° F (1005 K). At temperatures of 1600° F (1144 K) and higher N155 has the worst oxidation problem of any of the wire alloys studied. Even for a 100-micrometer pore diameter, there is an 80 percent reduction in flow in 300 hours at 1800° F (1255 K), as shown in figure 3(e-1).

Of the four alloys investigated only TD nickel-chromium shows measurable oxidation at 1400° F (1033 K) in figure 3. However, at higher temperatures such as 2000° F (1367 K) it is the best of the four alloys. For all initial pore sizes studied the TD nickel-chromium shows only a slightly greater pore closure rate at 2000° F (1367 K) than at 1800° F (1255 K) and is the only material which appears not to undergo complete pore closure within 600 hours at 2000° F (1367 K), within the range of pore sizes studied. When figures 3(a) to (e) are compared on the basis of percent flow reduction after 600 hours exposure, TD nickel-chromium is also the best alloy at 1800° F (1255 K). All the alloys show almost complete closure with 10-micrometer pores. With 40-micrometer pores, flow reductions in 600 hours at 1800° F (1255 K) from figure 3(d) are 58, 69, 70, and 100 percent for TD nickel-chromium, DH242, Hastelloy X, and N155, respectively. The 100-micrometer pore diameter material for the same conditions shows 28, 35, 39, and 100 percent for the same alloys in the same order in figure 3(e).

Driver-Harris 242 is clearly the best of the four alloys for operation at 1600° F (1144 K). With 10-micrometer-diameter pores the percent flow reductions in figure 3(a) are 78, 92, 94, and 98 for DH242, Hastelloy X, TD nickel-chromium, and N155,

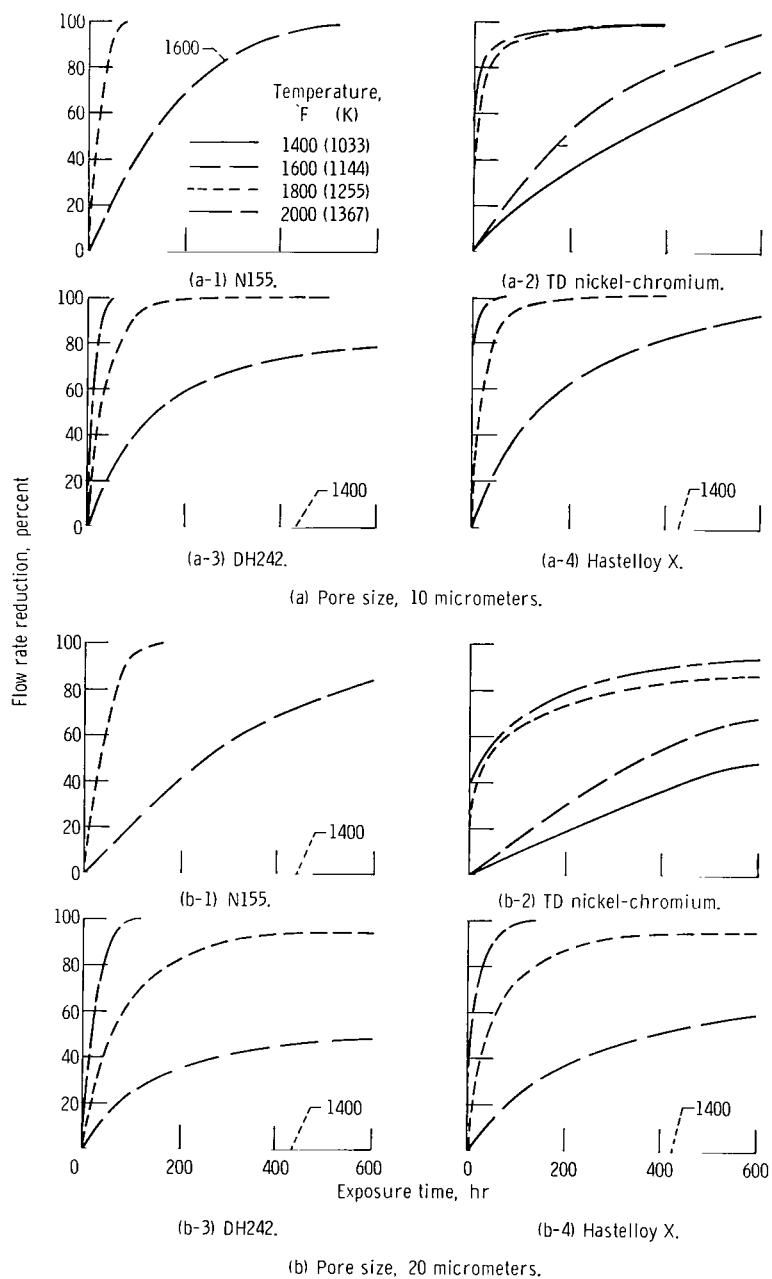


Figure 3. - Effect of oxidation on airflow through wire-form porous sheet with various-size pores.

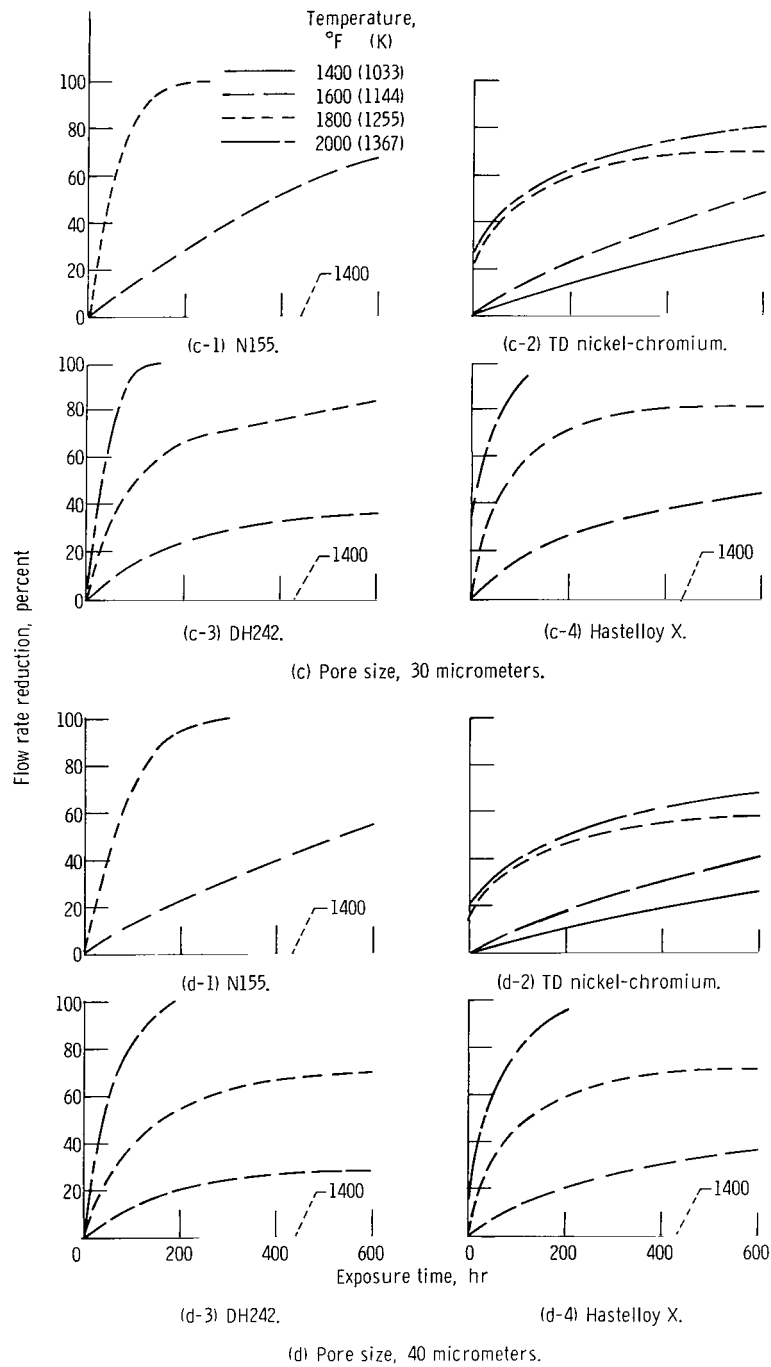
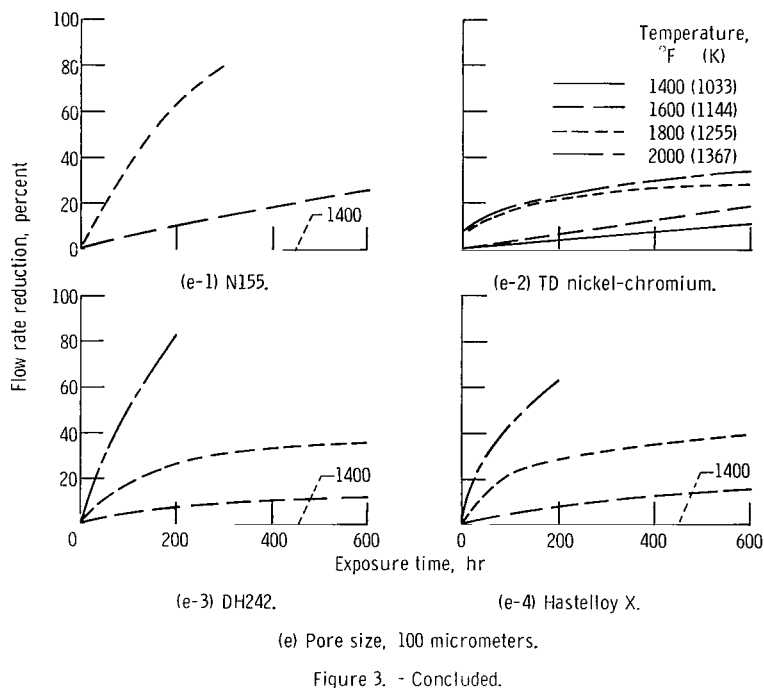


Figure 3. - Continued.



respectively, after 600 hours. The 100-micrometer-diameter material has percent reductions after 600 hours at 1600° F (1144 K) (fig. 3(e)) of 12, 15, 19, and 26 for these alloys in the same order as previously.

Comparison of Analytical Results with Experimental Data

Experimental oxidation data for wound wire-form porous sheet fabricated from TD nickel-chromium, DH242, and Hastelloy X are shown in figures 4 to 6, respectively. The TD nickel-chromium and DH242 oxidation tests were conducted by the Filter Division of the Bendix Corporation under contract with NASA (NAS3-10491). The Hastelloy X tests were run by the Allison Division of General Motors Corporation also under a NASA contract and are reported in reference 6. Average initial flow rates were 2.94 scfm/in.² (2.15 m/sec) for the TD nickel-chromium, 4.26 scfm/in.² (3.12 m/sec) for the DH242, and 1.6 scfm/in.² (1.17 m/sec) for the Hastelloy X materials. Filtration ratings from figure 2 for these airflow rates are about 20, 30, and 10 micrometers for the TD nickel-chromium, DH242, and Hastelloy X, respectively.

In figures 4 to 6, the experimental data were compared with the applicable analytical curves derived for the alloy, temperature, and pore size in figures 3(b), (c), and (a), respectively. The agreement between data and predictions is fairly good consid-

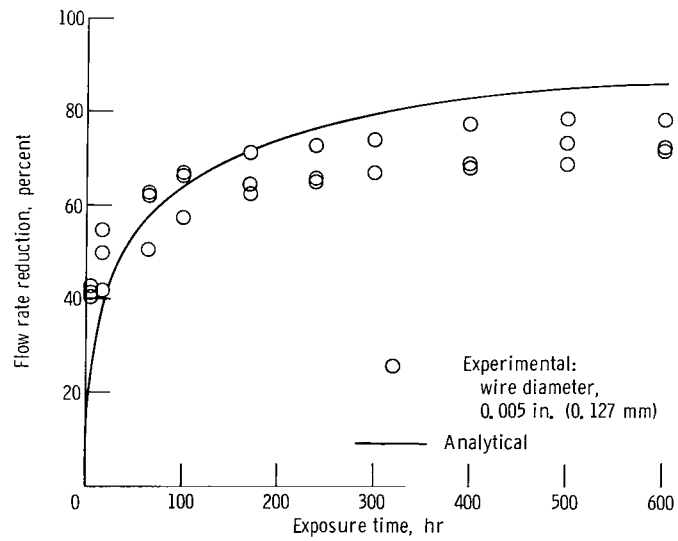


Figure 4. - Comparison of analytical results for TD nickel-chromium wire-form porous sheet with Bendix oxidation test data at 1800° F (1255 K).

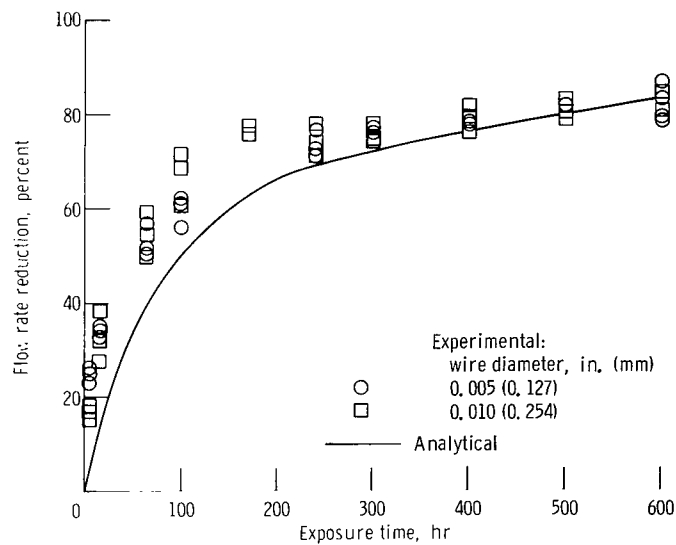


Figure 5. - Comparison of analytical results for DH242 wire-form porous sheet with Bendix oxidation test data at 1800° F (1255 K).

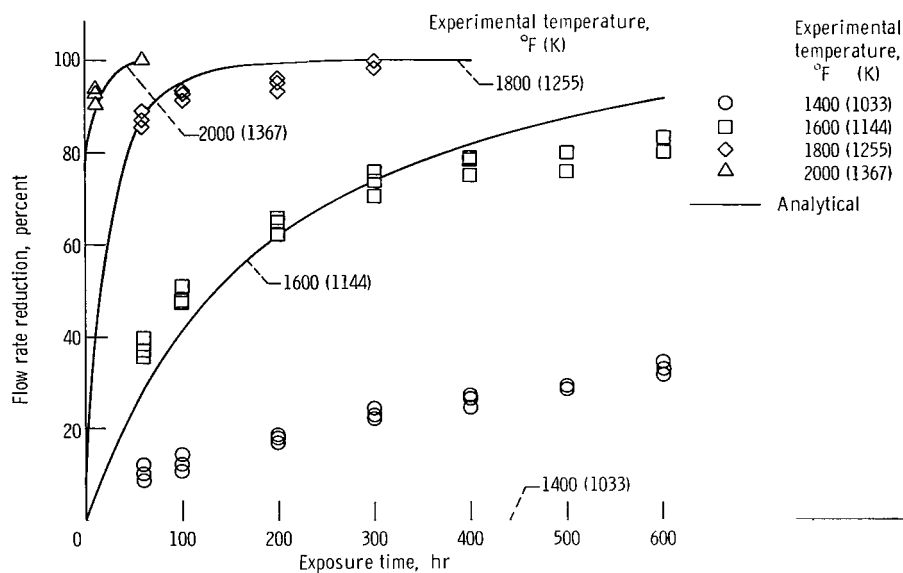


Figure 6. - Comparison of analytical results for Hastelloy X wire-form porous sheet with Allison (ref. 6) oxidation test data at 1400°, 1600°, 1800°, and 2000° F (1033, 1144, 1255, and 1367 K).

ering the scatter of the wire oxidation data of table I and the approximate nature of the information on the material pore sizes. The most serious discrepancy occurs at 1400° F (1033 K) for Hastelloy X in figure 6 where the experimental data show over a 30 percent flow reduction while the analytical results show no closure. However, a 30 percent flow reduction for a 10-micrometer pore would mean that the change in wire diameter was about 0.000035 inch (0.0008 mm), whereas the wire diameter data of reference 3 are only reported to the nearest 0.0001 inch (0.00254 mm).

From the comparisons of the experimental and calculated results shown in figures 4 to 6 it appears that the procedure of utilizing wire oxidation data and applying it to a capillary flow model as discussed previously gives reasonable predictions of the flow reduction caused by oxidation of wire-form porous materials.

Analytical Comparison of Porous Materials at 1800° F (1255 K)

The analytical results of figure 3 are used to compare the four alloys at a metal temperature of 1800° F in figure 7. The basis of comparison is the required pore size for acceptable flow restrictions of 20 and 50 percent over a range of exposure time from 0 to 600 hours.

As discussed previously, the largest absolute filtration size for the advanced air breathing engine requirements is about 32 micrometers. It is shown in figure 7 that

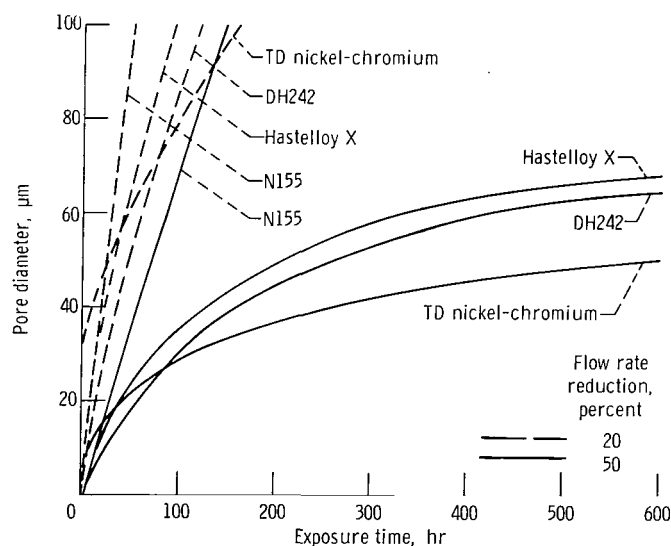


Figure 7. - Effect of pore size on time to 20 and 50 percent flow reduction at 1800° F (1255 K).

all of the alloys with 32-micrometer pores show 20 percent flow restriction within 25 hours, and that all of them show at least 50 percent restriction within 200 hours.

In order to have less than 50 percent flow reduction for 600 hours at 1800° F (1255 K), 50-micrometer pores are required for TD nickel-chromium, 70-micrometer pores for DH242, and 80-micrometer pores for Hastelloy X material. None of the alloys considered herein show less than 20 percent flow reduction for 150 hours, even with 100-micrometer pores. Woven wire-form porous sheet can also be used for transpiration cooled blades. Based on the results herein these materials appear even less suitable than the wound wire-form materials because the former require finer pores for the same permeability than the wire-wound materials as shown by the permeability-filtration rating data of reference 5. It therefore appears that none of the alloys considered herein possess sufficient oxidation resistance at 1800° F (1255 K) within the permeability range required for transpiration cooling of turbine blades for advanced air breathing engines.

Effect of Preoxidizing Porous Materials

In spite of the pessimistic outlook that the results of this investigation indicate for wire-form porous sheet of N155, TD nickel-chromium, DH242, or Hastelloy X there remains a further possibility of utilizing these materials for transpiration cooling with

an 1800⁰ F (1255 K) metal temperature. It may be feasible to allow the material to preoxidize to a desired pore size after which there would be relatively little oxidation. The essential condition that must be met for this procedure to be practicable is that the final pore size after oxidation stabilization be consistent with the design flow rate.

That this procedure may be suitable for blades designed for lives less than about 1000 hours is shown by the experimental data of figure 4 where the TD nickel-chromium flow rate degradation for a material temperature of 1800⁰ F (1255 K) is greatly reduced after about 200 hours of oxidation time. However, the Poroloy material would have to be made to a higher initial permeability to achieve a stabilized condition within the flow rate design range. The DH242 experimental data of figure 5 also seems to be leveling out but at a much slower rate than the TD nickel-chromium. As has been mentioned previously, a further superiority of the TD nickel-chromium is that it shows only a slightly greater pore closure rate at 2000⁰ F (1367 K) than at 1800⁰ F (1255 K) and, therefore, would be less susceptible to accelerated oxidation due to either a hot spot or partial pore closure.

CONCLUSIONS

The following general conclusions were drawn from the results of this study of the flow rate reduction caused by the oxidation of wire-form porous sheet for the transpiration cooling of turbine blades for advanced air breathing engines:

1. The analytical procedure for predicting the reduction in flow through wire-form porous sheet subject to oxidation using cyclic and steady-state wire oxidation data with a capillary model and pore sizes based on absolute filtration ratings from bead tests appears to be validated. Agreement between the analytical results of the present report and experimental results for wound wire-form porous materials from other investigators is generally good.

2. None of the alloys considered has sufficient oxidation resistance to be used at 1800⁰ F (1255 K). TD nickel-chromium, which shows the best oxidation resistance at 1800⁰ F (1255 K), requires 50-micrometer-diameter pores to limit the reduction in flow to 50 percent in 600 hours. Based on the flow rate - absolute filtration rating relation used, wound wire-form porous material with pore sizes 32 micrometers or smaller will be necessary to meet the design coolant flow requirements for advanced air breathing engines. TD nickel-chromium also has the best oxidation resistance above 1800⁰ F (1255 K). Since its oxidation rate at 2000⁰ F (1367 K) is only slightly higher than at 1800⁰ F (1255 K), it is less susceptible to accelerated oxidation resulting from a rise in metal temperature above 1800⁰ F (1255 K).

3. Wound wire-form porous materials fabricated from Driver-Harris 242 appear practicable for metal temperatures up to 1600⁰ F (1144 K). The analytical results predict that Driver-Harris 242 will not have significant pore closure for exposure times up to 600 hours at 1600⁰ F (1144 K).

4. There is a possibility that wound wire-form porous materials can be preoxidized to a relatively stable pore size which will give airflow rates within the design requirements.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 12, 1968,
126-15-02-41-22.

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TABLE I. - WIRE SPECIMEN OXIDATION DATA

Alloy	Temper- ature		Exposure time, hr	Cyclic		Static		Adjusted			
				Wire diameter increase							
	°F	K		in.	mm	in.	mm	in.	mm		
N155	1400	1033	4	0	0	-----	-----	0	0		
			16	↓	↓	-----	-----	↓	↓		
			64			-----	-----				
			100			0	0				
			200			-----	-----				
			300			-----	-----				
			400			-----	-----				
			500			-----	-----				
			600	↓	↓	-----	-----	↓	↓		
	1600	1144	4	0	0	-----	-----	-----	-----		
			16	↓	↓	-----	-----	-----	-----		
			64			-----	-----	-----	-----		
			100			0.0001	0.0025	-----	-----		
			200			-----	-----	-----	-----		
			300			-----	-----	-----	-----		
			400	0.0002	0.0051	-----	-----	0.0002	0.0051		
			500	.0002	.0051	-----	-----	.0002	.0051		
			600	.0003	.0076	-----	-----	.0003	.0076		
	1800	1255	4	0.0001	0.0025	-----	-----	0.0001	0.0025		
			16	.0002	.0051	-----	-----	.0002	.0051		
			64	.0002	.0051	-----	-----	.0002	.0051		
			100	.0002	.0051	0.002	0.0051	.0002	.0051		
			200	.0005	.0125	-----	-----	.0005	.0125		
			300	.0013	.0330	-----	-----	.0013	.0330		
400			.0028	.0711	-----	-----	.0028	.0711			
TD-NiCr			1400	1033	4	0	0	-----	-----	0	0
					16	↓	↓	-----	-----	↓	↓
	64					-----	-----				
	100					0	0				
	200					-----	-----				
	300	↓			↓	-----	-----	↓	↓		
	400	0.0001			0.0025	-----	-----	0.0001	0.0025		
	500	.0001			.0025	-----	-----	.0001	.0025		
	600	.0001			.0025	-----	-----	.0001	.0025		

TABLE I. - Continued. WIRE SPECIMEN OXIDATION DATA

Alloy	Temper- ature		Exposure time, hr	Cyclic		Static		Adjusted	
	°F	K		Wire diameter increase					
				in.	mm	in.	mm	in.	mm
TD-NiCr	1600	1144	4	-----	-----	-----	-----	0	0
			16	-----	-----	-----	-----	0	0
			64	0.0001	0.0025	-----	-----	0.0001	0.0025
			100	↓	↓	0.0001	0.0025	↓	↓
			200	-----	-----	-----	-----	-----	-----
			300	-----	-----	-----	-----	-----	-----
			400	-----	-----	-----	-----	-----	-----
			500	-----	-----	-----	-----	-----	-----
			600	.0002	.0051	-----	-----	.0002	.0051
	1800	1255	4	0	0	-----	-----	0	0
			16	0.0001	0.0025	-----	-----	0.0001	0.0025
			64	.0002	.0051	-----	-----	.0002	.0051
			100	.0002	.0051	0.0002	0.0051	.0002	.0051
			200	.0002	.0051	-----	-----	.0002	.0051
			300	.0003	.0076	-----	-----	.0003	.0076
			400	↓	↓	-----	-----	↓	↓
			500	-----	-----	-----	-----	-----	-----
			600	↓	↓	-----	-----	↓	↓
	2000	1367	4	0.0001	0.0025	-----	-----	0.000125	0.0032
			16	.0002	.0051	-----	-----	.000125	.0032
			64	↓	↓	-----	-----	.00025	.0064
			100	-----	-----	0.0003	0.0076	↓	↓
			200	-----	-----	-----	-----	-----	-----
			300	↓	↓	-----	-----	↓	↓
			400	0.0003	0.0076	-----	-----	0.000375	0.0095
			500	0.0003	.0076	-----	-----	.000375	.0095
			600	0.0003	.0076	-----	-----	.000375	.0095
DH242	1400	1033	4	0	0	-----	-----	0	0
			16	↓	↓	-----	-----	↓	↓
			64	-----	-----	-----	-----	-----	-----
			100	-----	-----	0	0	-----	-----
			200	-----	-----	-----	-----	-----	-----
			300	-----	-----	-----	-----	-----	-----
			400	-----	-----	-----	-----	-----	-----
			500	-----	-----	-----	-----	-----	-----
			600	↓	↓	-----	-----	↓	↓

TABLE I. - Continued. WIRE SPECIMEN OXIDATION DATA

Alloy	Temper- ature		Exposure time, hr	Cyclic		Static		Adjusted	
	°F	K		Wire diameter increase					
				in.	mm	in.	mm	in.	mm
DH242	1600	1144	4	0	0	-----	-----	0.0001	0.0025
			16	↓	↓	-----	-----	↓	↓
			64	↓	↓	-----	-----	↓	↓
			100	↓	↓	0.0002	0.0051	↓	↓
			200	↓	↓	-----	-----	↓	↓
			300	↓	↓	-----	-----	↓	↓
			400	↓	↓	-----	-----	↓	↓
			500	↓	↓	-----	-----	↓	↓
			600	↓	↓	-----	-----	↓	↓
	1800	1255	4	0	0	-----	-----	0	0
			16	0.0001	0.0025	-----	-----	0.0002	0.0051
			64	↓	↓	-----	-----	↓	↓
			100	↓	↓	0.0003	0.0076	↓	↓
			200	↓	↓	-----	-----	↓	↓
			300	0	0	-----	-----	-----	-----
			400	0.0002	0.0051	-----	-----	0.0004	0.0102
			500	.0002	.0051	-----	-----	.0004	.0102
			600	.0002	.0051	-----	-----	.0004	.0102
	2000	1367	4	0.0001	0.0025	-----	-----	0.0001	0.0025
			16	.0002	.0051	-----	-----	.0002	.0051
			64	.0002	.0051	-----	-----	.0002	.0051
			100	.0006	.0152	0.0005	0.0127	.0006	.0152
			200	.0014	.0356	-----	-----	.0014	.0356
Hastelloy X	1400	1033	4	0	0	-----	-----	0	0
			16	↓	↓	-----	-----	↓	↓
			64	↓	↓	-----	-----	↓	↓
			100	↓	↓	0	0	↓	↓
			200	↓	↓	-----	-----	↓	↓
			300	↓	↓	-----	-----	↓	↓
			400	↓	↓	-----	-----	↓	↓
			500	↓	↓	-----	-----	↓	↓
			600	↓	↓	-----	-----	↓	↓

TABLE I. - Concluded. WIRE SPECIMEN OXIDATION DATA

Alloy	Temper- ature		Exposure time, hr	Cyclic		Static		Adjusted	
	°F	K		Wire diameter increase					
				in.	mm	in.	mm	in.	mm
Hastelloy X	1600	1144	4	0	0	-----	-----	-----	-----
			16	↓	↓	-----	-----	-----	-----
			64	↓	↓	-----	-----	-----	-----
			100	↓	↓	0.0001	0.0025	-----	-----
			200	↓	↓	-----	-----	-----	-----
			300	↓	↓	-----	-----	-----	-----
			400	0.0001	0.0025	-----	-----	0.00015	0.0038
			500	.0001	.0025	-----	-----	.00015	.0038
	600	.0001	.0025	-----	-----	.00015	.0038		
	1800	1255	4	0	0	-----	-----	0	0
			16	0	0	-----	-----	0	0
			64	0.0001	0.0025	-----	-----	0.0002	0.0051
			100	.0001	.0025	0.0003	0.0076	.0002	.0051
			200	.0002	.0051	-----	-----	.0004	.0102
			300	.0002	.0051	-----	-----	.0004	.0102
			400	↓	↓	-----	-----	↓	↓
			500	↓	↓	-----	-----	↓	↓
	600	↓	↓	-----	-----	↓	↓		
	2000	1367	4	0.0001	0.0025	-----	-----	0.00015	0.0038
			16	.0002	.0051	-----	-----	.0003	.0076
			64	.0002	.0051	-----	-----	.0003	.0076
			100	.0003	.0076	0.0006	0.0152	.00045	.0114
			200	.0006	.0152	-----	-----	.0009	.0229
			200	.0006	.0152	-----	-----	.0009	.0229

TABLE II. - ALLOY NOMINAL CHEMICAL COMPOSITIONS

Alloy	Nominal chemical composition, wt. %										
	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Fe	Other
N155	0.15	1.50	0.50	21.0	20.0	20.0	3.0	2.5	1.0	Balance	0.15 N
TD nickel-chromium	0	0	0	20.0	Balance	0	0	0	0	0	2.0 ThO ₂
DH242	0	0	0	20.0	Balance	0	0	0	1.0	0	None
Hastelloy X	.10	.50	.50	22.0	Balance	1.5	9.0	.6	0	18.5	None

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